TECHNICAL REPORT

Efficient Thermoelectric Power Conversion of Waste Heat for Deployed Forces

SERDP Project EW-1651

AUGUST 2009

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Technical Report: Efficient Thermoelectric Power Conversion of Waste Heat for Deployed Forces (SERDP)
SI-1651

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August 24, 2009

The team of RTI International (RTI) and D-STAR Engineering (D-STAR) and our government partner US Army CERDEC (CERDEC) are pleased to provide SERDP this technical report for the program entitled *"Efficient Thermoelectric Power Conversion of Waste Heat for Deployed Forces (SI-1651)"*. This report will focus on the state of the waste heat conversion system at the end of the first proposed phase of the three-phase program and look forward to designs that could address issues encountered in the first phase. This report will first build an appropriate background based on data to show the evolution of the expected performance of the waste heat recovery system over phase 1. What will be shown are the changes in expected thermoelectric device efficiency and power output based on the actual available ΔT from the specific 3kW TQG that the team has procured for this program. This analysis will culminate in an estimation of the maximum power output with current technology for thermoelectric conversion and heat exchangers. Following this analysis, the actual performance of the phase 1 system will be discussed including power output and system level integration issues encountered and the lessons learned in the program. Finally, this report will show initial designs for future work that could address many of the issues encountered in phase 1 that could be used for future success on such a program.

Data was gathered on the generator set during the course of phase 1, which the team had to react to in the design and expectations for the heat recovery system. The most important piece of data was the lower available ΔT that was measured which caused the team to lower expectations for efficiency of the thermoelectric (TE) convertor. Also, some changes in power output targets for each phase are requested after analysis of the generator exhaust heat content has shown that the ability to reach the original targets may not be possible.

As a starting point, the following is an excerpt from the response made to SERDP following the SAB meeting:
<u>Response to comments immediately following original SAB meeting:</u>

- Plan to develop target conversion efficiency metrics for specific T-hot/T-cold temperatures, in addition to the power generation metrics, for each Go/No-Go decision point. T-cold should be a realistically achievable temperature in the field. *Based on the information from CERDEC, the temperature of the exhaust stream is ~525°C* with ambient conditions at 50°C. With these parameters, the two most promising options are shown in the table below:*

* 525°C exhaust temperature was expected to lead to a thermoelectric device hot-side temperature of ~450°C based on a temperature drop across the hot-side heat exchanger

Cold-side Heat Exchanger	Cold-Side Temp (°C)	Hot-Side Temp (°C)	Thermoelectric Conversion Device	Expected Conversion Efficiency (%)
Forced Air	~80	450	PbTe/TAGS bulk device	~10-11
Liquid heat exchanger using on-board fuel	~60	450	PbTe/TAGS bulk device cascade with Bi_2Te_3-based SL device	~11-12

Of course, with lower ambient temperatures, the expected conversion efficiency would increase. The expected conversion efficiencies and power levels for each Go/No-Go decision point are shown below (as a function of the success of thermoelectric device integration):

Phase	Target Hot-Side Temperature (°C)	Target Cold-Side Temperature (°C)	Target Power Level (W)	Target Conversion Efficiency (%)
1	450	80	50	9
2	450	60	200	10
3	450	60	500	>10

As mentioned above, power levels and efficiencies will be directly tied to the device hot-side and cold-side temperatures attained through good thermal interfacing and heat exchanger type.

Early Phase 1 Characterization

First, the exhaust temperature quoted of ~525°C came from informal discussions with CERDEC and was always meant to be a guide for expected performance. Of course the plan was to procure a generator for the program and base the system design on its characterization. The issue here is that specific performance metrics were put in place following the SAB meeting when real data was not available. Recently, CERDEC has been tasked with finding temperature data for the 3kW TQG and has been unable to find it. It seems the report written by the Army office (ATEC) does not include the data and the test occurred so long in the past that the original data is not available. However, the issue is that when a generator set was procured and characterized, we moved forward to design a system to meet the power goals of phase 1 with the real temperatures as our guide. The real exhaust gas temperature was found to be ~450°C[†] at full load. This apparent decrease of ~75°C in expected hot-side temperature forced the team to reevaluate the system based on a lower TE device conversion efficiency. However, D-STAR did manage to measure ambient temperatures inside the generator enclosure at ~50°C, very close to the CERDEC numbers, so we believed that a cold-side temperature of 80°C was possible with air cooling.

Another aspect was the power targets for each phase. As the above comments following the SAB meeting showed, the power targets for each phase were set at 50W for phase 1 and 200W and 500W for each of the subsequent phases. The targets for phase 2 and 3 were the maximum power outputs from the ranges set forth in the proposal. However, after an analysis of the heat

[†]450°C exhaust temperature was expected to lead to a thermoelectric device hot-side temperature of ~400°C based on a temperature drop across the hot-side heat exchanger

content in the generator set was made, which is shown below in the Table below, it was seen that the goal of 500W for phase 3 would be unobtainable based on the TE conversion efficiency (even in a best case scenario of larger ΔT as shown I the table) and the available heat in the exhaust gas. This concern was communicated in the annual report from January 2009 and repeated at the IPR briefing in February 2009. Below is a summary of that data which has been modified from the original presentation to show the original power level goals and better represent current possible ΔT:

Phase 1 Annual Report and IPR Data:

- CERDEC data on 3kW TQG shows that it is ~24% fuel efficient at full load (12.5kW heat input and 9.5kW waste heat) – ***estimate only ½ of waste heat in exhaust = 4.75kW***
- Thermal efficiency = converting available waste heat to that of heat into thermoelectric device
- Converter efficiency = converting heat into TE device to electricity

	Phase 1	Original Phase 2	Proposed Phase 2	Original Phase 3	Proposed Phase 3
TE Output Power Target	50W	200W	150W	500W	300W
TE Device Configuration	1-Stage PbTe/TAGS	2-Stage PbTe/TAGS : Bi2Te3	2-Stage PbTe/TAGS : Bi2Te3	2-Stage PbTe/TAGS : Bi2Te3	2-Stage PbTe/TAGS : Bi2Te3
TE Converter Efficiency Target	7.5%	10%	9%	10%	10%
ΔT Needed for Target Efficiency	325K	325K	275K	325K	325K
Required Thermal Efficiency	14%	42%	35%	105%	63%
Fuel Efficiency Increase	1.7%	6.6%	5.0%	10%	10%

As can be seen in the Table above, to meet the 500W goal in phase 3 would mean the capture of more heat than exists in the exhaust gas. So, the team requests to set the new metrics for pahse 2 and 3 at 150W and 300W respectively. Take note above the phase 2 power output targets are lowered slightly from the response to the SAB comments and the Phase 3 target are consistent with a 10% fuel efficiency gain.

Phase 1 Progress:

Based on these conditions, the team moved forward to design and fabricate the necessary hardware to conduct the phase 1 demonstration. *As can be seen in the table below, the lab-scale performance of the individual components, defined as the TE converter and the heat exchangers, have performed near the Phase 1 goal targets. However, the integration of all the components on the generator has led to lower performance mostly due to much smaller ΔT.* The available ΔT is decreased due to lower performance of the heat exchangers in the generator environment

as the maximum ΔT at a generator load of 3.0kW is only 215K, 2/3 the designed goal. Since thermoelectric power output is proportional ~ $(\Delta T)^2$, that is why the device efficiency is less than half of the expected value. Contributing to the lower ΔT is not only the differences in hot- and cold-side temperatures from designed values, but the transfer of ΔT to the thermoelectric device. Issues in integration can lead to parasitic drops of ΔT in interfaces due, in part, to the mechanical coupling of hot and cold heat exchangers with the thermoelectric device as a stressed member. The current configuration does not allow for repeatable and quantifiable pressure to be put on the devices, so this has led to some degradation of ΔT across the device. However, we have approaches to improve the performance with a more optimized design which will be discussed later in this white paper. So, we have component level performance meeting design specifications while the system level integration is suffering some losses.

	TE Converter	Thermal Efficiency	System Fuel Efficiency Increase
Phase 1 Goal	7.5% @ ΔT~325K (T_{hot}~400°C, T_{cold}~75°C)	14% (665W of heat flow)	1.7%
Lab-Scale Performance	**7.6% @ ΔT~325K (T_{hot}~400°C, T_{cold}~75°C)**	**11% (512W of heat flow)**	N/A
Integrated System Performance	3.3% @ ΔT~215K (8.3W) (T_{hot}~350°C, T_{cold}~135°C) (%ΔT~67%)	5.3% (251W of heat flow)	0.3%

With the first phase testing completed at RTI, the generator set along with devices and accompanying testing hardware were taken to Ft. Belvoir for a demonstration on April 1-3, 2009. During the demonstration at Ft. Belvoir, testing produced only ~1.5 Watts of power. There were some issues that will be discussed later that contributed to this low power output, however, although the testing results were well below the phase 1 goal of 50 Watts, CERDEC considers this work first-in-class. All thermoelectric work performed previously under CERDEC programs was burner-fed, this is the first waste heat generator of its kind integrated with an Army TQG.

<u>Phase 1 Analysis – System Challenges</u>

The following is a discussion of the systematic challenges faced by the team in obtaining the 50W Phase 1 Goal. As stated above, the maximum power achieved at RTI during system testing was 8.3 Watts. As a guide to the reader, a schematic of the phase 1 system is shown below as Figure 1. First, the air-cooled heat exchanger was not sufficient to lower T_{cold} below 135°C, ~55K higher than designed target of 80°C. Also, the small area hot-side heat exchanger was not able to recover enough heat. The hot-side temperature of ~350°C is ~ 50K lower than designed target of 400°C. Consequently, the overall ΔT was lowered from designed goal of 320K to 215K, causing much lower efficiency and power output from the TE device. Beyond the lower ΔT present in the absolute hot- and cold-side temperatures, the Arctic Silver interfaces are responsible for large thermal parasitics which show themselves as drops in ΔT outside of the TE device. The system is estimated to have dropped ~35% of ΔT across these parasitic interfaces as

measured by device voltage output. Analysis of the power output in conjunction with the lower external ΔT caused by heat exchanger issues and the loss of internal ΔT due to interfaces equal nearly exactly the thermal losses to produce 50 Watts. Therefore, the thermoelectric devices would have met the phase 1 goal of 50 Watts if the thermal issues at the system level could have been mediated.

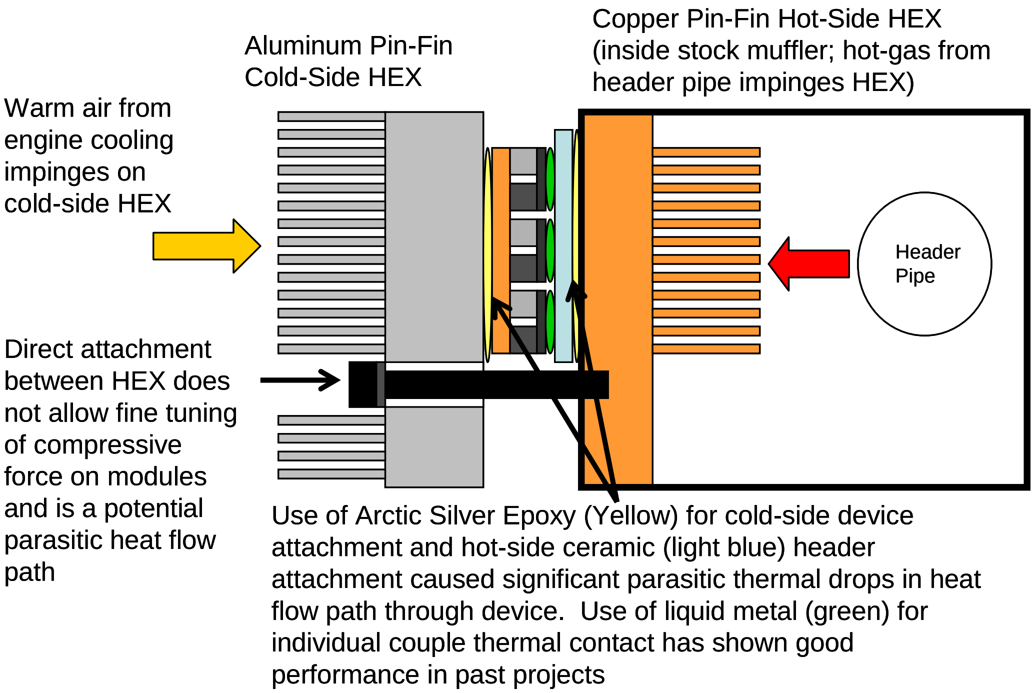

Figure 1 – Phase 1 system schematic

In regards to the arctic silver interface, the interface has been used in testing at RTI with good results. RTI has been looking at compliant, high-temperature thermal interfaces since the DARPA/ONR supported DTEC program and found that arctic silver can provide for good thermal interfaces. Of course, the use of liquid metal has been shown to be an excellent interface material, but initial use in this program showed that the system allowed too much movement of the individual parts and so a "hard bonding" approach was sought. Arctic silver was selected from past experience but it must be stated that there is a lack of high-temperature compliant thermal interface materials. However, issues with arctic silver also arose as demonstrated in Figure 2. Before and after test shows interface was not ideal. As can be seen in Figure 2, the regions of darker AlN means that the arctic silver interface is good, while lighter areas, after test, show that these interfaces failed during the temperature cycling. This fundamental

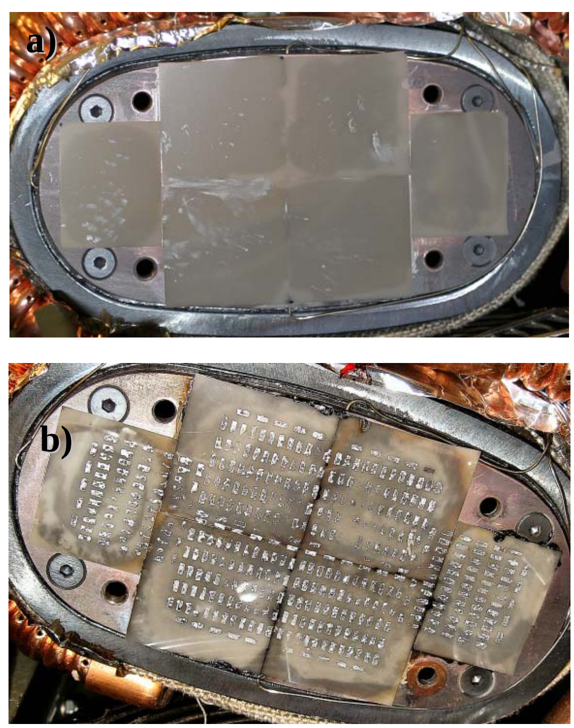

Figure 2 – Arctic silver interface seen through the AlN secondary hot-side header before (a) and after (b) testing showing the loss of interfacial integrity

system integration issue showed a complete failure during the testing at CERDEC, as shown below in Figure 3, where power production suffered more with a maximum power output of ~1.5 Watts. As Figure 3 shows, the arctic silver interface failed completely as the AlN secondary headers are shown on the module/cold-side heat exchanger side and come completely detached from the hot-side heat exchanger where they were originally mounted with arctic silver. Also contributing to the lower power output at CERDEC is that the air cooling plumbing had failed (fallen from engine air cooling exit) during the demonstration. This lack of forced air on the cold-side heat exchanger pushed T_{cold} to ~ 175°C, even higher than as tested at RTI.

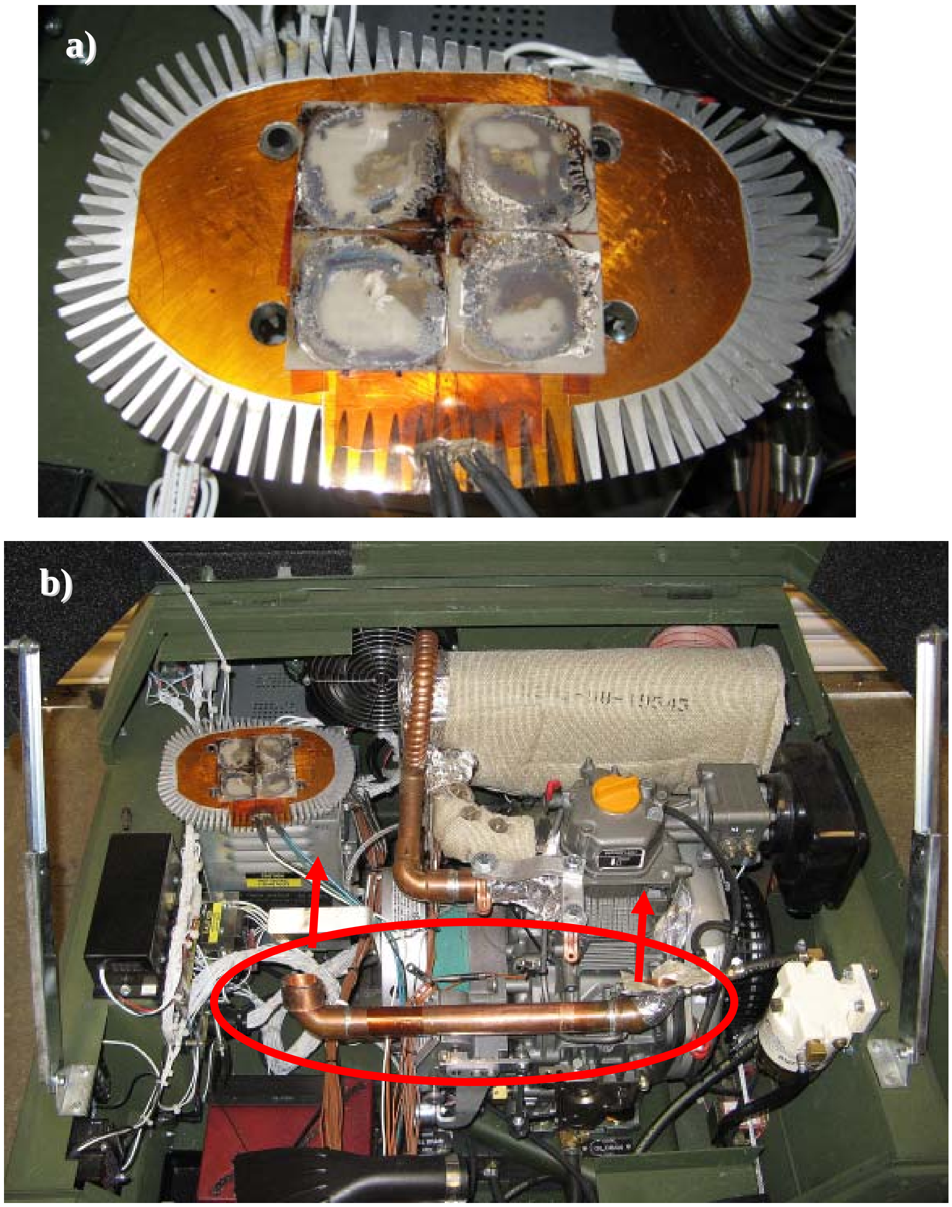

Figure 3 – Two major system failures occurred during testing at CERDEC, a) arctic silver interface between AlN secondary headers and the hot-side heat exchanger and b) the mechanical failure of the cold-side forced air plumbing that increased the cold-side temperature to 175°C

<u>Phase 1 Analysis – Program Delays Limited Iterations for Testing of System Integration</u>

Task Name	Start	Finish
EFFICIENT THERMOELECRIC POWER CONVERSION OF WASTE HEAT FOR DEPLOYED FORCES	*Mon 3/3/08*	*Tue 2/1/11*
Initial Fact Sheet	Mon 3/3/08	Mon 3/3/08
Final Fact Sheet	Tue 2/1/11	Tue 2/1/11
⊟ **Repeated Project Deliverables**	**Tue 4/1/08**	**Tue 2/1/11**
⊞ **Quarterly Progress Report**	**Thu 5/1/08**	**Mon 11/1/10**
⊞ **Monthly Finanacial Report**	**Tue 4/1/08**	**Tue 2/1/11**
⊞ **Annual Technical Report**	**Mon 12/1/08**	**Wed 12/1/10**
⊟ **Year 1 25-100 Watt Demonstration**	**Thu 5/1/08**	**Thu 4/30/09**
Kick-off Meeting at RTI	Fri 6/27/08	Fri 6/27/08
⊟ **Initial design of TE devcies for 100 Watts**	**Thu 5/1/08**	**Tue 9/30/08**
Initial experiments with single- and 2-stage devices with varying cold side temperatures - RTI	Thu 5/1/08	Fri 8/29/08
Select TE device type (single- vs 2-stage) - RTI	Mon 9/1/08	Tue 9/30/08
Collect initial specificiation of 3kW Generator	Tue 7/1/08	Tue 9/30/08
Actual Collect initial specification of 3kW Generator	Fri 9/19/08	Thu 10/30/08
Initial Design of Heat Exchangers and test fixture - RTI / D-STAR	Wed 10/1/08	Wed 12/31/08
Actual Initial Design of Heat Exchangers and test fixture	Wed 10/8/08	Mon 12/15/08
Build TE modules, heat exchangers, and test fixtrue - RTI / D-STAR	Wed 10/1/08	Wed 12/31/08
Actual Build TE modules, heat exchangers and test fixt	Wed 12/17/08	Fri 2/13/09
Testing at RTI - RTI	Thu 1/1/09	Fri 2/27/09
Actual Testing at RTI	Mon 2/16/09	Tue 3/31/09
Testing at CERDEC - RTI / CERDEC	Mon 3/2/09	Wed 4/15/09
Year 1 Summary Meeting	Wed 4/15/09	Wed 4/15/09
Go/No-Go Descision for Year 2	Thu 4/30/09	Thu 4/30/09

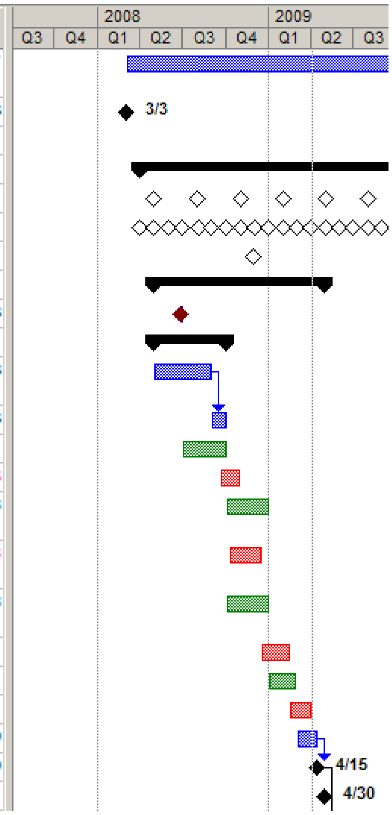

Figure 4 – Gant chart showing original program plan as well as the actual program timing showing that the late arrival of the generator set pushed critical tasks ~ 1-2 months later in phase 1as well as shipment of generator set back to D-STAR for air flow modifications contributed to small amount of time with integration of system at RTI.

Contributing to the state of the phase 1 final testing at RTI and CERDEC was the constricted timeline for system integration and testing due to the delays encountered in the procurement of the generator set as well as the onset of system integration and testing at RTI. Below is a summary of the timeline of the system level integration and testing:

- October 2008 – Characterization of 3kW TQG showed lower exhaust gas temperature than given by CERDEC
- January 2009 – Initial system testing at RTI showed cold-side temperature ~70K higher than expected
- February 2009 – System testing at RTI with added air flow additions by D-STAR showed improvement in cold-side temperature, but still ~50K too high.
- March/April 2009 – Final testing at RTI and CERDEC showed reduced performance versus expectations: Design = 50W, Actual = 8W
  - Evaluation at CERDEC, with unknown transport issues, and cited failures produced ~1.5W of output power

Overall, the team did not have sufficient time to try multiple integration trials and apply engineering solutions to increase the power output of the phase 1 demonstration.

The following is an overview of the major issues facing the team during the Phase 1 work and the initial expected pathway for improvement:

- Phase 1 integration delayed due to late arrival of TQG, HEX parts from D-STAR and subsequent shipping of TQG back to D-STAR for air flow modifications. The delay did not allow for the multiple iterations that were needed for engineering demonstration. **Improvement in phase 2 will be based on:**
  - **Better management of timelines in phase 2**
  - **Back-up HEX supplier to be explored by RTI (most likely Creare, Inc. or Modine Manufacturing) as part of an aggressive approach to a tough problem of capturing waste heat**
- Initial integration using liquid metal for thermal interface showed that the headers needed to be secured due to vertical surfaces of designed system and vibration issues. Arctic Silver was used for thermal interfaces (after consideration of many materials), which proved to be a liability. **Improvements in phase 2 will be based on:**
  - **Design of horizontal device placement as RTI integration experience has been with horizontal surfaces in MIPS, DTEC and ITECC.**
  - **Will use liquid metal at all interfaces in phase 2.**
  - **Use vibration isolation for phase 2 integration to reduce forces on system**
- Use of molybdenum device headers on the device necessitates use of insulating header on hot-side of device – **Improvement in phase 2 will be based on:**
  - **Recent RTI development of ceramic-based device headers may allow direct connection to hot-side surface without an intermediate header.**
  - **Phase 2 design will allow both options**
- Lack of lower-temperature air impingement on cold-side HEX allowed the cold-side temperature to exceed expectations. **Improvement in phase 2 will be based on:**
  - **Use of liquid cooling to achieve lowest cold-side temperature**
  - **Will enable use of 2-stage device for higher thermoelectric conversion efficiency**
- Lack of area of hot-side pin fins on HEX allowed for the hot-side temperature to be depressed under operation with TE devices – **Improvement in phase 2 will be based on:**
  - **Phase 2 HEX will replace current muffler and allow for using full area to capture heat will allow maximizing hot-side temperature while still controlling sound output.**
- Attachment of cold-side HEX directly to hot-side HEX gave problems in quantifying compressive force across the device for best thermal connection and provided possible heat leak path to cold-side of device. **Improvement in phase 2 will be based on:**
  - **Use through bolts and two cold-side HEX for cold-to-cold attachment for reduction in thermal stress on attachment hardware which will allow the quantification of the compressive force on devices**
  - **Do direct connection of cold-side and hot-side, except through thermoelectric device, will maximize power output and efficiency**

Phase 2 Description, Goals and Intermediate Milestones

Based on the above analysis of phase 1 and the solutions advanced, a phase 2 design can be sketched out. Figure 5 shows a schematic of the phase 2 design that addressed all the major issues faced in phase 1.

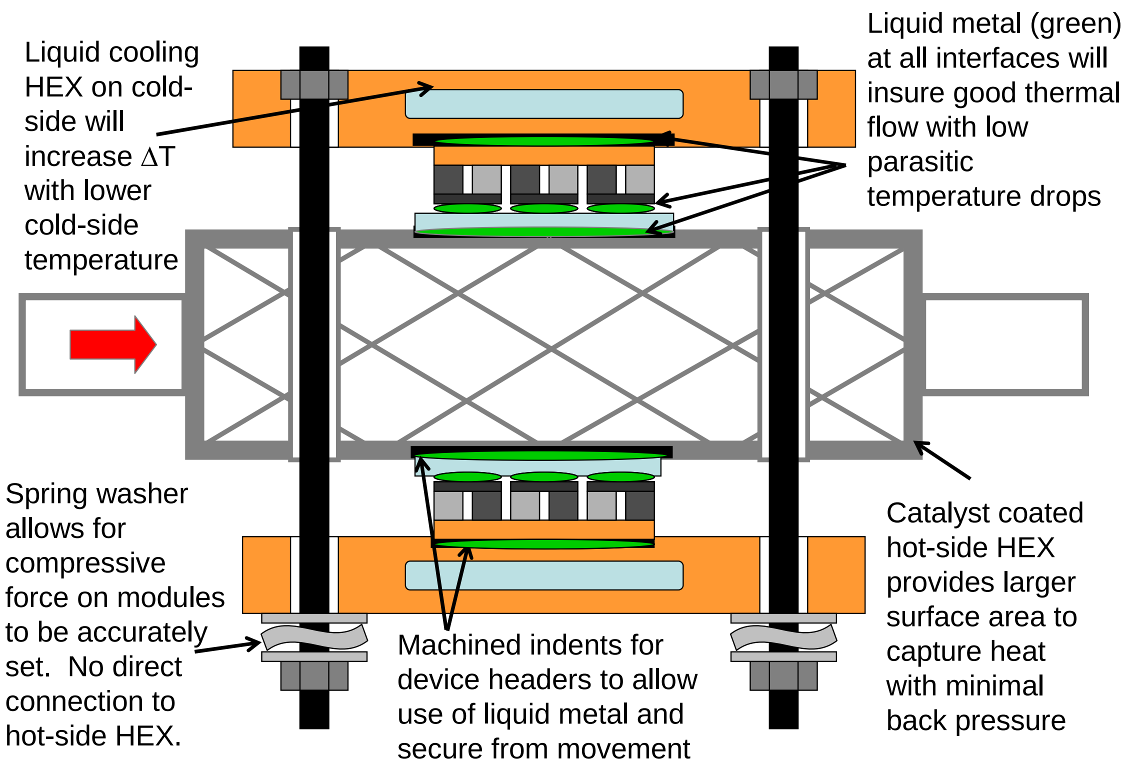

Figure 5 – Phase 2 system schematic showing flexible mount to engine exhaust and TQG case to lower vibration in heat recovery system while maintaining muffler function of the system.

Looking forward to phases 2 and 3, a better picture of the expected performance based on all available data can be given for the component and system level of the waste heat recovery program. Moving to a 2-stage device in phases 2 and 3 would most likely necessitate using liquid cooling of some kind, as mentioned in the original SAB comments, to produce the similar ΔT, but with a cold-side temperature nearer to 60°C instead of 80°C. A new chart is presented below in order to understand what our goals will be for the two future phases with more detail and better understanding of the ΔT possible in the current generator set. The power output targets are net power and would not reflect any needed TE device power to operate ancillary cooling loop components. This additional power requirements would be part of the phase 2 design plan for the use of liquid cooling, however, initial research has led to the belief that this power requirement would not be in excess of 25 Watts and potentially much less. These designs would also use an optimized heat exchanger design to completely replace the stock muffler/exhaust system that would incorporate higher performance heat exchangers as well as quantifiable compression methods to give the best opportunity of maximizing heat transfer to/from the devices. *The table shows that the team will meet the 10% efficiency goal with less ΔT by using better heat exchanger design and system integration to capture the waste heat in the*

exhaust. We will still keep the option of adding a catalyst to the hot-side heat exchanger to increase hot-side temperature as well. As ambient temperatures rise, this performance would be de-rated to a certain extent that we would like to measure in the following phases.

Expected Performance in Phase 2 and 3

	Phase 2	Phase 3
TE Output Power Target	150W	300W
TE Device Configuration	2-Stage PbTe/TAGS: Bi_2Te_3	2-Stage PbTe/TAGS: Bi_2Te_3
TE Converter Efficiency Target	9.0%	10%
ΔT Needed for Target Efficiency	275K	325K
T_{hot}	335°C	385°C
T_{cold}	60°C	60°C
Heat Rejection Method	Liquid-Cooling	Liquid-Cooling
Required Thermal Efficiency	35%	63%
Fuel Efficiency Increase	5.0%	10%

Our team partners at CERDEC have found an Army study of the operational use of the 3kW TQG and reported the following:

3kW TQG Fuel Consumption and Load Profile

Load	Fuel Cons	Mission Profile	Mission Fuel Cons	Mission Load	Exhaust Temp
kW	*gal/hr*	*hrs*	*gal*	*kWh*	*degF*
0	0.103	0.00	0	0	525
0.75	0.18	4.60	0.828	3.45	625
1.5	0.224	7.25	1.624	10.875	775
2.25	0.281	7.25	2.03725	16.3125	725
3	0.353	4.60	1.6238	13.8	850

MISSION DATA: 23.7 hrs/day operation	
6.11305	gal/day mission
0.257935	gal/hr mission
44.4375	kWh/day
1.875	**kW AVG mission**
745.1477	**degF AVG mission**

Usign the above data with the characteristics of the efficiency of the generator set (which shows efficiency of 24% at full load and 21.5% at 1.875kW load) and assuming a heat recovery of ~63% of the exhaust gas, the following table can be shown as a guide to the average performance of the waste heat recovery system. The table shows that the average operation would still provide a large amount of power, 180 Watts, with a significant increase in fuel efficiency.

Phase 3 requested power goal at full 3kW load vs average load of 1.875kW

Generator Load	3.0kW	1.875kW
TE Device Configuration	2-Stage PbTe/TAGS: Bi_2Te_3	2-Stage PbTe/TAGS: Bi_2Te_3
Exhaust Temperature	450°C	400°C
T_{hot}	385°C	340°C
T_{cold}	60°C	50°C
ΔT Available	325K	290K
TE Converter Efficiency	10%	8.5%
TE Output Power	300W	180W
Fuel Efficiency Increase	10%	6%

The final conclusion that the team would like to put forward is that thermoelectric waste heat recovery is a task that is very dependent on system integration and heat exchanger performance. Also, the performance will be driven by the amount of heat in the exhaust stream and the quality of that heat. However, thermoelectric devices are up to the task of waste heat recovery and the continuation of programs such as these will allow the system integration issues to be resolved and allow for larger and more efficient waste heat recovery units to become used in a wide array of environments. Furthermore, as thermoelectric power conversion efficiency continues to increase, programs like this one, will be even more important to already having he initial issues resolved and prepare for these much higher performing thermoelectric devices.